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Augmentation of the Neutronic Safety Aspect of High-Density Fuel Research Reactor Using New Control Element Design

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Date: 2025-03-10T00:00:00+00:00

Abstract

The user wants me to translate a scientific text from Simplified Chinese to English. However, the text provided is already in English. Let me re-read the instructions carefully.

The user says: "The development of research reactors is expanding to make this industry more economically viable in various fields. One of these areas involves increasing the density of fissile material in fuel. This research emphasizes the importance of paying attention to fuels with a high density of fissile material by examining the silicide plate fuel for core arrangement. The study introduces a new idea and design to enhance two neutronic safety design criteria, specifically the Power Peaking Factor (PPF) and Stuck Rod Shutdown Margin (SRSM) for a standard 10 MW research reactor. Increasing the number of irradiation boxes in the core center results in the maximum flux being distributed over a larger area, reducing PPF. Additionally, leveraging the high moderating ratio of D2O and, in a new design, using a thin layer of D2O in the control assembly has raised the worth of the control rod, allowing for reactor control without the need to increase the amount of absorbent material. Moreover, the results of the reactivity coefficient calculations confirm that the implementation of heavy water within the control assembly does not detract from the overall safety of the reactor system."

Wait, this is English text. But the instructions say "Translate from Simplified Chinese to English". Let me check if there's any Chinese text that I missed. No, the entire content is in English.

Looking at the instructions again: - "Translate from Simplified Chinese to English with the highest accuracy and academic tone." - The user provided English text.

This is contradictory. The user asks for translation from Chinese to English, but provides English text. I need to check if this is a test or if there's a misunderstanding.

Let me re-examine the prompt. The user says "The development of research reactors is expanding…" which is clearly English. But the instructions say to translate from Simplified Chinese to English.

Perhaps the user made a mistake and pasted the English version instead of the Chinese version. Or perhaps they want me to "translate" it in the sense of improving the academic tone and style, even though it's already in English.

Given the strict requirements about preserving LaTeX commands, tags, etc., and the fact that the text contains none of these, I should probably just return the text as-is, since it's already in English. But that seems odd.

Wait, let me check the system prompt again. It says I'm a "professional scientific translator specializing in academic papers. Translate from Simplified Chinese to English…"

But the user message is in English. This is confusing. Let me think about what the user might actually want:

1. They might have made a mistake and provided the English text instead of Chinese text.
2. They might want me to "translate" it in a metaphor

Full Text

Preamble

Augmentation of the Neutronic Safety Aspect of High-Density Fuel Research Reactor Using New Control Element Design

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Abstract

The development of research reactors is expanding to enhance economic viability across various applications. One key approach involves increasing the density of fissile material in fuel. This research emphasizes the importance of high-density fissile fuels by examining silicide plate fuel for core arrangement. The study introduces a novel design to enhance two critical neutronic safety criteria: the Power Peaking Factor (PPF) and Stuck Rod Shutdown Margin (SRSM) for a standard 10 MW research reactor. Increasing the number of irradiation boxes in the core center distributes the maximum flux over a larger area, thereby reducing PPF. Additionally, leveraging the high moderating ratio of D_2O, a thin layer of heavy water was incorporated into the control assembly, which increased control

rod worth without requiring additional absorber material. Reactivity coefficient calculations confirm that implementing heavy water within the control assembly does not compromise overall reactor safety.

Keywords: Neutronic Safety Margin, High-Density Fuel, Power Peaking Factor, Stuck Rod

1. Introduction

Today, the cost-effectiveness of the nuclear industry represents a fundamental question that must be addressed based on required outputs. Investors in the nuclear industry are particularly focused on the economic viability of research reactors, which play crucial roles in nuclear applications. A key industry challenge is the selection of nuclear fuel as the primary basis for energy production. Consequently, research has focused on developing fuels with low enrichment and higher fissile material density, emphasizing peaceful applications while preventing nuclear weapons proliferation.

Most research reactors for materials testing operate at high power levels (\$ 10*MW*).*Theprimaryobjectiveindevelopingnewfuelsistoachievehigherpowerandneutronfluxlevelsoverlong* [**?**, **?**]. Due to these higher power densities, materials with high heat transfer coefficients are essential. Aluminum alloys, with a heat transfer coefficient of 180 W/mK, are primary candidates for fuel cladding compared to zirconium alloy at 10 W/mK [**?**].

Since fuel temperature significantly affects reactivity fluctuations, high-power-density research reactors should have smaller heat-producing volumes to achieve uniform thermal profiles. This is achievable with plate fuel, which is easier to design due to aluminum's excellent malleability.

As shown in Table 1 , the trend toward high-density fuels is increasing. Silicide fuel has gained popularity for research reactors, especially those exceeding 10 MW, with approximately 82% of such reactors using plate-type fuel. Notably, silicide plate fuel demonstrates the highest utilization in terms of operating hours per year [**?**].

Table 2 shows annual reactor operating hours, where U_3Si_2-Al fuel achieves the most operation time above 4,000 hours per year [**?**]. This fuel type has been used in research reactors spanning a wide power range, from kilowatts to 125 megawatts. Low-enrichment silicide fuels with uranium density up to 4.8 g/cm^3 are currently used in 21 research reactors (up to 70 MW) across 13 countries, including France, Australia, and Canada. Technologies have been developed to maximize fuel density by increasing uranium silicide dispersion in the aluminum matrix to 4.8 g/cm^3 [**?**].

Several research reactors utilize U_3Si_2-Al plate fuel. The Reactor Serba Guna–Gerrit Augustinus Siwabessy (RSG-GAS) research reactor (30 MW) began its fuel conversion from oxide to silicide in 1997, with design and fuel management strategies for higher uranium loading implemented in 1998. That research investigated new fuel management strategies for silicide equilibrium cores with increased fuel loading (300 g at 3.55 g/cm^3 density and 350 g at 4.15 g/cm^3 density per fuel assembly) compared to previous oxide fuel (250 g at 2.96 g/cm^3 density), significantly extending reactor cycle length [?]. The China Advanced Research Reactor (CARR) operates at 60 MW with U_3Si_2-Al plate fuel at 19.75% enrichment, comprising 17 fuel assemblies and 4 hafnium control assemblies with fuel followers. This heavy water-reflected reactor achieves a thermal flux of 10^{15} n/cm$^2\cdot$s in the central channel [?].

The Japan Research Reactor-3 (JRR-3) is a pool-type reactor using light water as moderator and coolant, with beryllium and heavy water as reflectors. It operates at a maximum thermal power of 20 MW using low-enrichment (LEU) silicide fuel plates. The JRR-3 core consists of 26 standard fuel elements, 6 follower fuel elements with neutron absorbers, and 12 beryllium reflectors installed at the reactor pool bottom [?].

The South African Fundamental Atomic Research Installation (SAFARI-1) is a pool reactor operating at 20 MW nominal power, cooled by forced circulation of light water which also serves as moderator. The reactor core utilizes various arrangements of 24 to 32 fuel assemblies [?].

This research examines the advantages of silicide fuel compared to traditional fuels regarding neutronic parameters within a 10 MW research reactor core. Additionally, it evaluates the impact of central irradiation boxes on key design parameters such as PPF and SRSM. After determining an optimal core arrangement using the diffusion method [?], verification was conducted via the Monte Carlo method. Subsequently, neutronic feedback parameters—including fuel temperature, coolant temperature, and coolant density—were analyzed for a standard 10 MW reactor core. Furthermore, to ensure control rod effectiveness in the new neutronic and safety design, a thin layer of heavy water (D_2O) was examined at various positions near the control assembly absorber.

2. Material and Method

Due to high fuel production costs, the industry is shifting toward high-density fuels like silicide fuel compared to traditional alternatives. This shift results in less waste due to more compact cores and enables higher flux. The high generated flux allows broader reactor applications, including radiopharmaceutical production and fuel/materials testing. Therefore, this research selected silicide fuel plates (U_3Si_2-Al) with aluminum cladding.

Table 3 provides material specifications for SAFARI-1 plate LEU uranium-silicide fuel assemblies. As mentioned, 10 MW power is considered for neutronic design [?]. Figure 1

presents Standard Fuel Element (SFE) and Control Fuel Element (CFE) configurations.

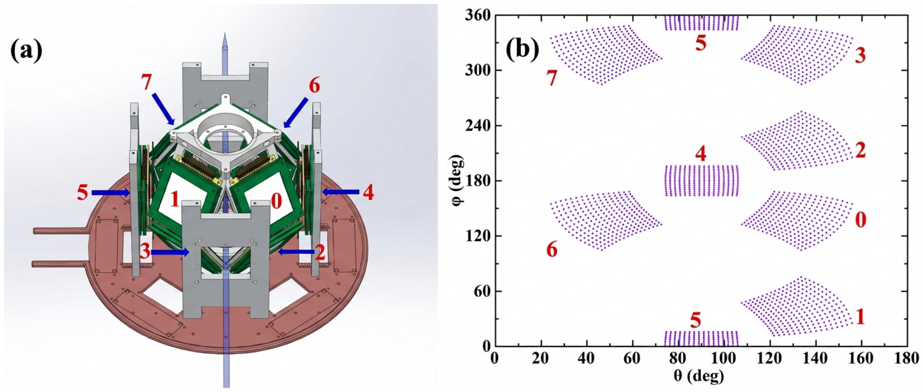

Figure 1: Figure 1

This research investigates neutronic parameters of silicide fuel in a 10 MW typical reactor for various core configurations. These parameters include effective multiplication factor (K_{eff}), excess reactivity (ρ_{ex}) (pcm), shutdown margin (SDM) (pcm), SRSM (pcm), total PPF, integral worth of control rods (IWCRs) (pcm), and safety reactivity factor (SRF). Additionally, estimating reactivity changes caused by variations in critical parameters—such as fuel meat temperature, moderator temperature, and moderator density—is essential for analyzing reactor behavior under normal and accident conditions. According to thermohydraulic criteria for integrating fuel and control assemblies, the most important factors are coolant flow rate, Power Peaking Factor (PPF), and inlet temperature. Therefore, the IAEA proposed a typical 10 MW core consisting of 20 fuel assemblies and 5 control assemblies [**?**]. This research aims to determine the optimal arrangement for a 10 MW power core.

In the first step, four different silicide fuel arrangements were investigated. To achieve high flux, embedding an irradiation box in the core center is crucial. As shown in Figure 2

, a core with a central irradiation box was examined using MCNP code. Subsequently, two, three, and four central irradiation boxes were added to the reactor core center. The two key neutronic design parameters are maximum PPF (PPF < 3) and maximum SRSM (less than -1000 pcm), which determine core acceptance from a neutronic perspective.

3.1 Neutronic Parameters Calculation

Neutronic parameters of a typical 10 MW reactor were investigated for different initial core configurations. These parameters include K_{eff}, ρ_{ex} (pcm), SDM (pcm), SRSM (pcm), PPF, IWCRs (pcm), and SRF. According to Table 4 , Core No. 4 better meets neutronic safety standards than other configurations, with significantly increased control rod worth. An important phenomenon occurring

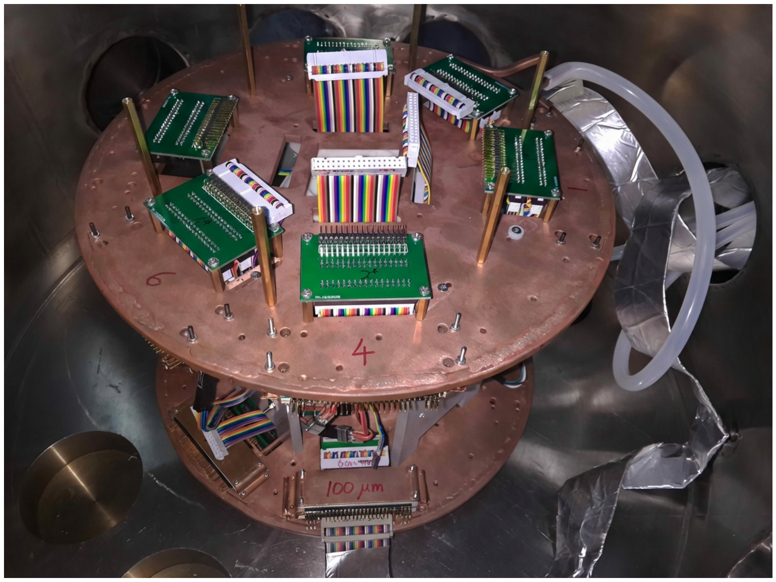

Figure 2: Figure 2

with increased central boxes is neutron flux shifting to the surroundings, resulting in broader flux distribution that reduces PPF and increases flux incident upon control rods.

However, adding central irradiation boxes replaces high-reactivity fuel, presenting the challenge of shortened cycle length. This effect is less pronounced with high-density silicide fuel compared to oxide (U_3O_8-Al). Requiring approximately 3400 pcm for transition from cold-clean to hot xenon conditions, the 3517 pcm excess reactivity in cold-clean states is insufficient for U_3O_8-Al fuel cores, preventing practical cycle initiation (Table 5). Given requirements for excess reactivity to accommodate experimental programs and ensure adequate cycle length, only 117 pcm remains at hot operation commencement, which proves insufficient.

Therefore, in addition to Core 4 shown in Figure 3

, two other cores with four central irradiation boxes were examined. The investigation required simultaneous satisfaction of excess reactivity and SRSM requirements. With 3400 pcm needed for cold-clean to hot xenon transition, core excess reactivity at cycle start must be significantly higher than 3400 pcm to achieve desired cycle length.

Considering excess reactivity and SRSM, Cores 5 and 6 were included for review alongside Core 4.

Table 6 shows neutronic parameter comparison results for these cores [**?**]. Since

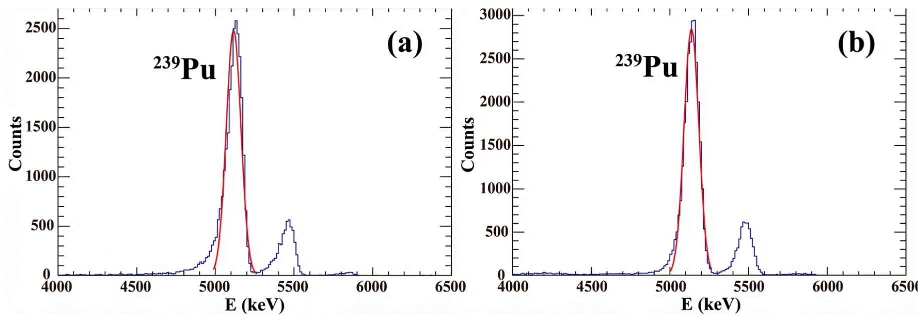

Figure 3: Figure 3

increased core excess reactivity decreases SRSM worth, Core 5 falls approximately 1600 pcm short of design criteria, while Core 6 is about 400 pcm short and Core 4 is 200 pcm short. To address this issue, heavy water is utilized around the absorber, as explained in the following section.

3.2 Effects of D_2O and H_2O Moderators on Neutronic Parameters

This research placed heavy water around the absorber to observe its impact on control plate worth. Two key points must be noted when using heavy water instead of light water.

First, heavy water has a smaller scattering cross-section and much longer migration length (D_2O: 174 cm, H_2O: 5.84 cm) compared to light water. This means neutrons in heavy water require larger volumes to reach thermal energies and induce fission. Therefore, if the available volume is not proportional to heavy water's migration length, excess reactivity reduction can occur in thermal spectrum reactors [**?**].

Second, heavy water has a lower absorption cross-section than light water in the thermal energy region. While heavy water might initially seem to increase excess reactivity, its large migration length relative to fuel assembly and reactor core dimensions in typical 10 MW reactors actually reduces excess reactivity. Conversely, using heavy water as a thin layer adjacent to control rods, due to its lower absorption cross-section, increases neutron fluence toward the control rod, thereby increasing control rod worth through enhanced absorption.

Figure 4

displays two configurations where heavy water replaces light water around the absorber plate. The two Control Fuel Element (CFE) structures were evaluated in Cores 4, 5, and 6, each containing four central radiation boxes. Table 7 presents calculated effects of adding heavy water in the control assembly for both structures. According to the table, D_2O increases neutron absorption by

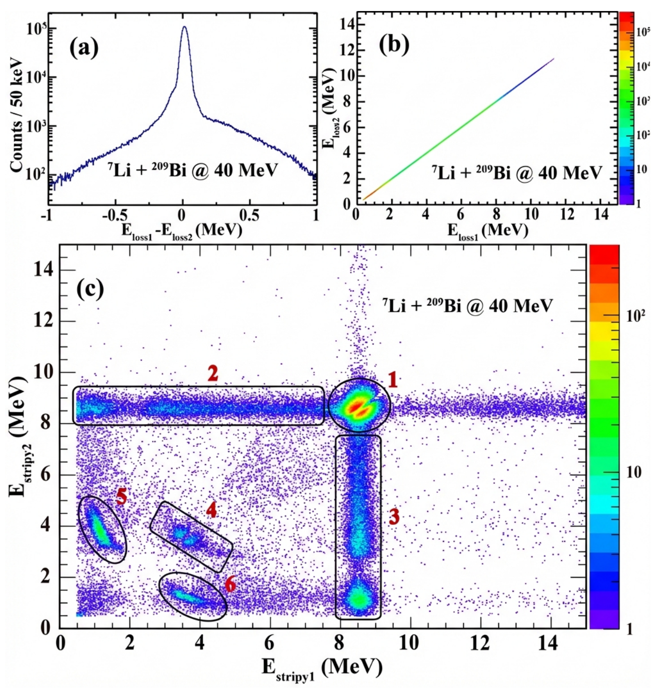

Figure 4: Figure 4

control rods. Additionally, SDM and SRSM values increase with heavy water presence, ultimately enhancing reactor safety.

Comparing these results with the previous state, adding heavy water increased control plate worth by -1000 pcm with Structure 1 and -30 pcm with Structure 2 in Core 4. For Core 5, increases were -960 pcm with Structure 1 and -391 pcm with Structure 2. For Core 6, increases were -1052 pcm with Structure 1 and -440 pcm with Structure 2.

Based on the results, Core 4 with Control Structure 1 and Core 6 with Control Structures 1 and 2 meet SRSM conditions. With a 3400 pcm transition cost from cold-clean to hot xenon state, Core 6 with Control Structure 2 provides the highest excess reactivity for hot xenon startup, resulting in longer cycle length.

3.3 Reactivity Feedback

Determining reactor behavior under normal and accident conditions requires estimating reactivity changes caused by variations in critical parameters, including fuel meat temperature, moderator temperature, and corresponding moderator density. Using CITATION code, Figures 5-8 present reactivity changes versus state variables for Core 4 configuration with both light water (H_2O) and heavy water (D_2O) moderators (Structure 2).

Figure 5

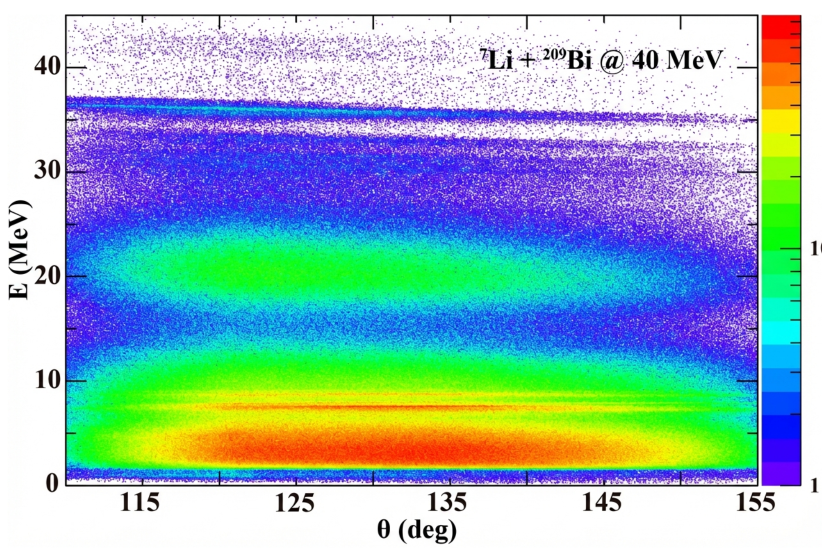

Figure 5: Figure 5

shows that increasing fuel temperature decreases reactivity due to Doppler effects. The results indicate fuel meat reactivity coefficients of -1.51 pcm/°C and -1.56 pcm/°C for H_2O and D_2O moderators, respectively.

Figure 6

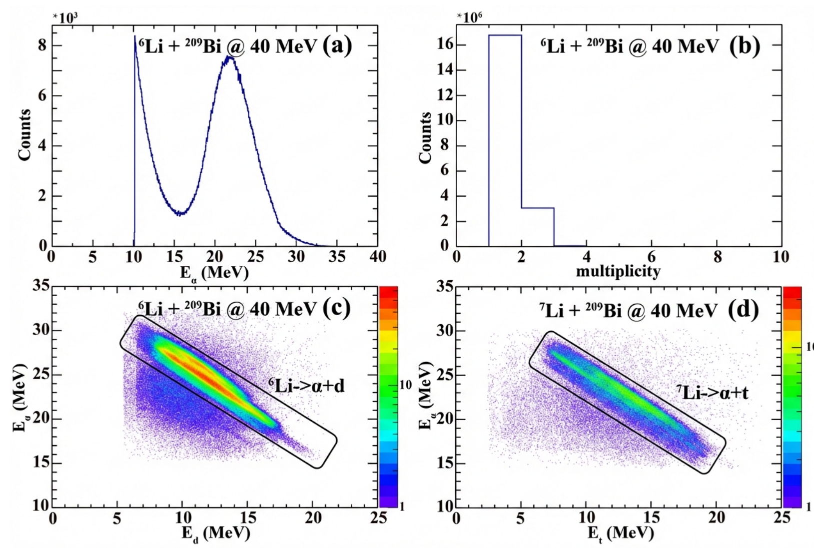

Figure 6: Figure 6

represents reactivity variation versus moderator temperature at constant moderator density. The key safety aspect is that moderator temperature coefficients at constant density are -7.26 pcm/°C and -7.24 pcm/°C for H_2O and D_2O moderators, respectively.

Figure 7

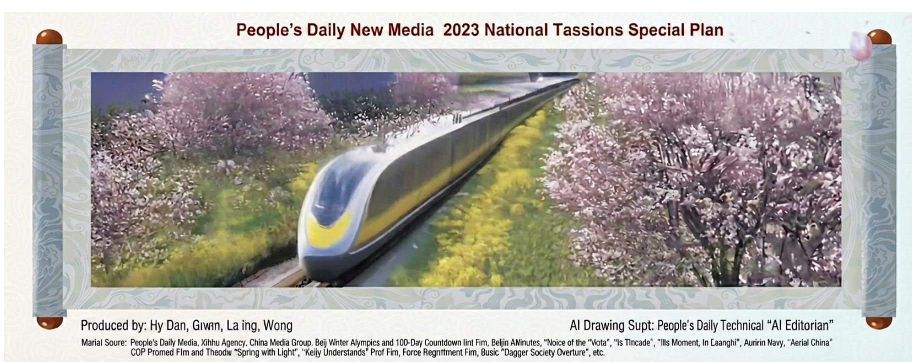

Figure 7: Figure 7

depicts moderator density effects on reactivity variation. The results confirm moderator density coefficients of -12.78 pcm/°C and -12.96 pcm/°C for H_2O and D_2O moderators, respectively.

Figure 8

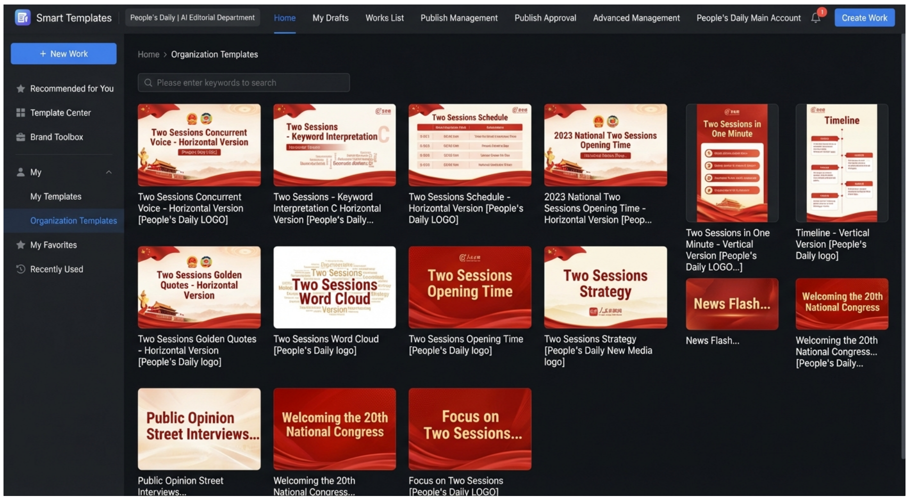

Figure 8: Figure 8

shows combined density and temperature variation effects on reactivity state. The calculated reactivity coefficients of -20.33 pcm/°C and -20.11 pcm/°C for H_2O and D_2O moderators, respectively, confirm the reactor's safe configuration.

4. Conclusion

This research focused on enhancing neutronic safety design of a typical 10 MW research reactor using high-density silicide fuel. The study investigated effects of increasing central irradiation boxes and using a thin D_2O layer in the control assembly on two neutronic safety criteria: PPF and SRSM. The research structure and accomplishments are outlined below.

First, neutronic design criteria and their challenges and solutions were investigated:

- **Power Peaking Factor**: High-power density in silicide-fueled reactors requires intelligent PPF management to avoid excessive heat generation in specific areas. The study found that increasing symmetrical irradiation boxes in the core center distributed maximum flux over a larger area, reducing PPF.
- **Stuck Rod Shutdown Margin (SRSM)**: Meeting the required SRSM criterion of -1000 pcm is crucial for ensuring safe reactor shutdown even with a stuck control rod. The study initially found SRSM insufficient for a core with four irradiation boxes. To address this, heavy water (D_2O) was investigated around the control rod absorber.

- **Increased Control Rod Worth**: D_2O's lower absorption cross-section compared to light water allows more neutrons to reach the control rod, increasing its worth.
- **Enhanced Safety Margins**: D_2O usage increased both SDM and SRSM, improving reactor safety.

The study analyzed reactivity changes due to fuel temperature, moderator density, and moderator temperature variations. Results indicate that the D_2O-incorporated reactor configuration maintains safe reactivity coefficients across all parameters, ensuring stable operation. Key findings include:

- **Optimal Core Configuration**: A core with four central irradiation boxes and a thin D_2O layer surrounding the control rod absorber meets safety criteria for both PPF and SRSM.
- **Improved Cycle Length**: D_2O usage in the control assembly, coupled with high-density silicide fuel, can contribute to longer operational cycles.
- **Enhanced Safety**: The study demonstrated that incorporating D_2O in the control assembly design significantly improves safety margins in typical 10 MW research reactors using silicide fuel.

This study examined the fresh core (first core). Future research will evaluate the equilibrium core with burned fuel starting from the presented core for specific applications.

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Figures

Figure 9: Figure 11

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Figure 10: Figure 12

Figure 11: Figure 13